

Estimating Storm Surge Risk along Balkan Coast: Methodologies, Models and Applications

Alfred Lako*¹, Ildir Lami², Sander Kovaci³

¹Department of Environmental Engineering, Polytechnic University of Tirana, Tirana, Albania.
Email: lakoalfred78@gmail.com | ORCID: <https://orcid.org/0009-0004-9164-3497>

²Department of Hydraulics and Hydrotechnics, Polytechnic University of Tirana, Tirana, Albania. Email: idlirlami28@gmail.com | ORCID: <https://orcid.org/0009-0004-4451-4481>

³Department of Mathematical Engineering, Polytechnic University of Tirana, Tirana, Albania.
Email: kovacisander563@gmail.com | ORCID: <https://orcid.org/0009-0002-4302-8954>

*Corresponding author

How to cite this paper: Lako, A., Lami, I. and Kovaci, S. (2025). Estimating Storm Surge Risk along Balkan Coast: Methodologies, Models and Applications. *Grassroots Journal of Natural Resources*, 8(1): 470-493. Doi: <https://doi.org/10.33002/nr2581.6853.080119>

Received: 25 February 2025

Reviewed: 31 March 2025

Provisionally Accepted: 03 April 2025

Revised: 08 April 2025

Finally Accepted: 10 April 2025

Published: 28 April 2025

Copyright © 2025 by author(s)

Publisher's Note: We stay neutral with regard to jurisdictional claims in published maps, permissions taken by authors and institutional affiliations.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
<http://creativecommons.org/licenses/by/4.0/>



Open Access

Executive (Chief) Editor
Dr. Hasrat Arjjumend
Associate Editors
Dr. Usongo Patience
Ms. Nejma Belarbi
Assistant Managing Editor
Mr. Kartik Omanakuttan



Abstract

The relevance of this study lies in its contribution to understanding storm surge dynamics and the development of effective coastal protection strategies, which are critical in mitigating the impact of climate change on vulnerable coastal ecosystems and infrastructure along the Balkan coast. The study aims to analyse methods for forecasting storm surges along the coast, assessing their impact on coastal ecosystems and developing effective protection measures, including the use of breakwaters and sediment budget assessment. This study used meteorological and hydrodynamic modelling, as well as geographical analysis and sediment budget estimation techniques, to predict and analyse the impact of storm surges on coastal areas. The study found that the most intense storm surge waves on the coast occur during winter and autumn, with the greatest risk to coastal ecosystems in the East Coast region. Numerical hydrodynamic modelling techniques in wave prediction models can accurately forecast wave height and direction, which greatly enhances the accuracy of storm surge predictions. The influence of shoreline morphology, including bottom slope and the presence of natural barriers, showed that the presence of coastal sandbanks and barrier reefs significantly reduces the strength of waves reaching land, thereby mitigating the effects of storms. Analyses of the impact of Rubble breakwaters confirmed their high effectiveness in reducing erosion and protecting the shoreline from damage, with structures orientated to wave patterns and bottom depth being the most successful. The sediment budget assessment showed that storm surges significantly change the distribution of sand masses along the coast, which affects the sustainability of coastal ecosystems and requires regular monitoring. The study confirmed the need for an integrated approach to storm surge forecasting and coastal protection, including the use of wave barriers, infrastructure adaptation and monitoring of changes in coastal morphology.

Keywords

Nearshore Wave Climate Methods; Storm Surge Prediction; Coastline Morphology; Wave Run-Up; Rouble Mound Breakwater; Sediment Budget

Introduction

Storm surges pose a serious threat to coastal ecosystems, infrastructure and populations, especially in areas prone to climate change. The Balkan coastline, with its diverse morphological features and high vulnerability to storm events, needs a thorough analysis of the risks associated with the effects of storm surges. These natural phenomena have the potential to cause significant damage, coastal erosion and landscape changes, which in turn have an impact on the ecological state of the region and its economy. Forecasting storm waves and assessing their impact requires state-of-the-art methods and models that can accurately predict their behaviour and develop effective coastal protection measures. Shoreline morphology, such as bottom depth, slope, and the presence of natural barriers, has a significant impact on wave strength, and structures such as Rubble breakwaters can significantly mitigate the effects of storms (Manno *et al.*, 2022). It is also important to consider sediment dynamics, as the transport and accumulation of sand masses along the coast play a key role in maintaining the stability of coastal ecosystems.

The problem of storm surges and their impact on coastal ecosystems in a changing climate is an important challenge for researchers in marine hydrodynamics and coastal defence (Fedonyuk *et al.*, 2020). Forecasting storm surges and evaluating their effects on coastal areas necessitates the study of a wide range of theoretical and empirical models. Dean's equilibrium beach profile theory (Dean, 1991) is a seminal contribution in coastal sediment dynamics, providing an analytical framework for forecasting the reaction of sandy beaches to wave energy input. This model aids in delineating the silt distribution and the morphological alterations of beaches during storm wave conditions. Its significance in contemporary applications is found in its incorporation into numerical coastal change prediction models and sediment transport simulations.

In addition to worldwide theoretical frameworks, research focused on the Balkan region is essential for comprehending the intricate dynamics of storm surges influenced by local geo-morphological and meteorological factors. Research conducted by Shisler and Johnson (2020) on the Montenegrin coast provided essential insights into the sedimentary effects of episodic storm surges on restricted coastal plains. Wei and Nguyen (2022) investigated historical storm surge occurrences along the northern Aegean coastline, pinpointing geological and anthropogenic factors that exacerbate coastal vulnerability. Görmüş and Ayat (2020) examined the geographical variability of coastal risks along the Romanian sector of the Black Sea, which, while not typically regarded as part of the central Balkan Peninsula, shares meteorological influences and sedimentary dynamics characteristic of the wider region. The regional contributions illustrate the heterogeneity in coastal reaction based on local bathymetry, land use, and previous shoreline management practices. These characteristics are essential for calibrating models for storm surge prediction and for constructing coastal defence measures.

Studies by Jordan and Fröhle (2022) have shown that the use of climate models to predict storm waves has helped to accurately estimate their intensity and potential impact on coastal ecosystems. The models developed by them also made it possible to account for seasonal and long-term changes in the climatic conditions of the region. The work of Trotta *et al.* (2021) focused on the application of hydrodynamic models to analyse the

interaction of waves with the coastline, taking into account its morphological features. This has significantly improved the accuracy of predictions, especially concerning changes in wave strength and direction under complex coastal shapes. Schmitt and Chaumillon (2023) investigated the effect of breakwaters on the effectiveness of coastal defence against storm waves and erosion. Their work proved that properly designed barriers can significantly reduce storm surge damage, ensuring the resilience of coastal ecosystems. Hamdi *et al.* (2023) studied the influence of shoreline morphology on storm wave propagation, proposing new methods for coastal stabilisation, including the use of natural and artificial barriers. These methods took into account not only the physical but also the ecological characteristics of coastal areas. McCarroll *et al.* (2021) evaluated the sediment budget along the coast, finding that storm waves play a key role in the transport and accumulation of sand masses. They proposed methods to predict changes in sediment distribution and their impact on coastal stability.

Griggs and Reguero (2021) investigated seasonal changes in the distribution of wave energy and their impact on the stability of coastal ecosystems. This allowed them to develop recommendations for adapting ecosystems to changing conditions and increasing their resilience to storm surge waves. Caloiero, Aristodemo and Ferraro (2022) stressed the importance of integrating climate data and coastal morphological characteristics in the development of comprehensive storm wave forecasting models. They proposed ways to improve prediction accuracy and develop adaptive coastal protection strategies. Musinguzi and Akbar (2021) analysed the effect of bottom depth and shoreline slope on wave strength and behaviour, which was crucial for storm surge risk assessment. Their work demonstrated how these parameters influenced the strength of waves reaching the coast.

Chang and Mori (2021) focused on the interaction of waves with natural barriers such as sandbanks and reefs, investigating their role in protecting against storm waves. Their results showed that such barriers could significantly reduce the impact of waves by reducing erosion processes. Tanim, Goharian, and Moradkhani (2022) emphasised wave forecasting in a changing climate, with a special focus on the adaptation of protective structures. Their research proposed methods for dynamically adjusting coastal defence approaches under global climate change. However, existing studies do not adequately capture the interaction of several factors such as seasonal variations, bottom depth, and coastal morphology, making it difficult to better predict storm surge impacts. In addition, more research is needed on the effectiveness of combined protective measures, including natural and man-made barriers, to provide long-term coastal protection in the face of climate change.

The study aimed to systematically analyse existing methodological approaches to storm surge forecasting, assess their effectiveness in the coastal areas of the peninsula and develop practical recommendations to improve the resilience of coastal areas to the negative impacts of such phenomena. Based on the facts presented above, the specific objectives of this study are as follows:

1. To review various wave forecasting models, including their accuracy and applicability to regional conditions.
2. To evaluate the impact of shoreline morphological features on wave propagation and storm surge strength.

3. To study the effectiveness of Rubble breakwaters in reducing erosion processes and protecting the coast from destruction.

Materials and Methods

This study employed a range of scientific methodologies to evaluate storm surge danger throughout the coastline, thoroughly evaluating potential risks and their effects on coastal ecosystems and infrastructure.

Meteorological Modelling

A primary method employed was meteorological modelling, which involved the analysis of various atmospheric parameters such as wind speed, direction, air pressure, and water temperature. These data were processed using advanced tools, such as the Weather Research and Forecasting model, which enables high-resolution simulations of atmospheric phenomena. This model integrates real-time meteorological data to simulate weather events and predict storm characteristics. In addition, the Global Forecast System model was used to generate global weather forecasts that provide insights into long-term climatic scenarios, essential for understanding the potential intensification of storm waves under changing climatic conditions. The data processed through these models were critical for determining the atmospheric parameters that contribute to storm wave generation. Furthermore, the modelling facilitated both short-term and long-term forecasts of storm frequency and intensity, helping to predict the future risk of coastal flooding and the intensity of storm surges.

Hydrodynamic Modelling

Hydrodynamic modelling was performed using analytical methods based on Sturm-Liouville equations to investigate wave propagation dynamics in nearshore situations (Daci, Tola, and Çepa, 2023). This methodology facilitated the examination of wave amplitude fluctuations and energy distribution as waves neared the shore, considering seabed topography and coastal configuration. While not employed as a numerical modelling instrument, the Sturm-Liouville framework offered insights into the amplification of wave motion in areas characterised by intricate shoreline topography.

Sediment Transport Modelling

The research additionally examined sediment transport mechanisms via mathematical modelling. The sediment budget analysis concentrated on assessing alterations in sand volume along the coastline resulting from storm events. This was accomplished by the application of formulas that take into account wave height, storm duration, and coastal material characteristics. The findings facilitated the identification of regions with significant erosion potential and those prone to sediment accumulation, both of which are essential for long-term coastal stability.

Shoreline Morphology Analysis

Shoreline morphology was analysed by geographical approaches that integrated data on bottom slope, depth, and the existence of both natural and artificial coastal structures, including sandbanks, barrier reefs, and breakwaters (Oraby *et al.*, 2024). The morphological features were evaluated for their capacity to either alleviate or exacerbate the effects of storm surges.

Assessment of Breakwater Efficacy

The efficacy of Rubble breakwaters was assessed by theoretical estimates of wave energy dissipation. The computations yielded estimations of wave height decrease following interaction with the structures and were utilised to evaluate their efficacy in safeguarding the shoreline against storm-induced erosion. The following formulae and equations were used in the study:

The equation of vibration of the medium (1):

$$\left(\lambda w(x) - q(x)\right)y = 0, \quad \frac{d}{dx} \left(p(x) \frac{dy}{dx} \right) + \quad (1)$$

where: y is a function describing the change in wave amplitude, $p(x)w(x)$, and $q(x)$ are coefficients that depend on the physical characteristics of the medium, and λ is an eigenvalue that determines the nature of the wave motion. This Sturm-Liouville equation was used to describe the variation of the wave amplitude y depending on the physical characteristics of the medium. Within the framework of the study, it was used to analyse wave processes and calculate the eigenvalues λ , which determined the character of wave motion in a given system.

Water level balance equation (2):

$$\Delta h = \int_0^t \left(\frac{Q_{in} - Q_{out}}{A} \right) dt, \quad (2)$$

where: Δh is the change in water level, Q_{in} and Q_{out} are the volumes of water inflow and outflow, and A is the water surface area. This equation was used to determine the change in water level, Δh as a function of inflow Q_{in} and outflow Q_{out} of water. It allowed estimating hydrological changes based on the dynamics of water flows and water surface area A .

A model of coastal sediment volumes (3):

$$M = k \cdot H_s^2 \cdot T, \quad (3)$$

where: M is sediment volume, H_s is wave height, T is storm duration, and k is a coefficient depending on material type and shoreline conditions. This formula was used to calculate coastal sediment volumes (M) as a function of wave height (H_s), storm duration (T) and a factor k that takes into account material properties and shoreline conditions. It was used to estimate erosion and sediment accumulation processes.

Wave height attenuation at the breakwater (4):

$$H = H_0 \left(1 - \frac{2h}{l}\right), \quad (4)$$

where: H – wave height after interaction with the breakwater, H_0 – initial wave height before interaction with the breakwater, h – breakwater height (or water depth at the installation site), L – wavelength. This formula describes the reduction in wave height (H) after interaction with the breakwater or in the shallow water zone. It was used in the study to evaluate the effectiveness of breakwaters in protecting the shoreline from wave action.

The equation of sediment diffusion in a stream (5):

$$D\Delta^2 C, \quad \frac{\partial C}{\partial t} + \Delta \cdot (vC) = \quad (5)$$

where: C – precipitation concentration, v – flow velocity (including currents and wave effects), D – diffusion coefficient, Δ^2 – Laplace operator (to describe spatial distribution). This transport equation was used to model the change in sediment concentration (C) due to fluxes (v) and diffusion (D). It has been used to describe the spatial and temporal distribution of sediment in water streams or coastal zones.

Results

The Impact of Storm Surges on the Balkan Coastline

Storm surges along the Balkan coastline pose a serious threat to coastal ecosystems, infrastructure and human activities. Due to the geographical position of the Balkan Peninsula, its coastline is exposed to various climatic phenomena such as storms, strong winds and high waves, which significantly influence the formation of coastal conditions. Storm surges, resulting from factors such as changes in atmospheric pressure, the effects of ocean currents and seasonal variations in water temperature, lead to a significant rise in water levels and increased wave activity. The Balkan coastline is characterized by a variety of morphological features, such as beaches, river deltas and coastal cliffs, which play an important role in the propagation and intensity of storm surges (Çoni and Madhi, 2023; Shahini *et al.*, 2022). For example, in areas with flatter shores, waves may weaken as they approach the coast, whereas in steeper areas, wave energy is concentrated, which can cause significant damage. Also, important is the influence of barrier reefs and man-made structures such as breakwaters, which can both mitigate and amplify the effects of storms depending on their location and condition.

Storm surges can cause significant coastal change, erosion of sandy beaches and destruction of infrastructure, including residential and tourist areas. This is particularly relevant for countries with developed tourism, such as Albania, Croatia and Greece, where coastal resilience has a direct impact on the economy of the region. In addition, storm surges can have serious impacts on ecosystems, causing degradation of coastal ecosystems, destruction of vegetation and loss of species (Shumka *et al.*, 2020). Coastal wave climate plays an important role in the ecology and safety of coastal zones

(Miloslavić *et al.*, 2012; Skliar *et al.*, 2023). Understanding how wave activity varies with climatic conditions helps to better predict impacts on coastal ecosystems, infrastructure, and populations. The study of wave climate involves a variety of techniques such as meteorological modelling, observations of climate changes and hydrodynamic modelling. These approaches provide scientists with extensive data and accurate risk assessments of coastal waves.

Techniques for Storm Surge Forecasting and Coastal Protection

Meteorological modelling is an important tool for predicting weather conditions that affect storm wave formation (Rusho *et al.*, 2024). Numerical models can account for many factors such as temperature, pressure, humidity and wind speed that combine to create wave activity. These models are used to predict extreme weather events that can produce storm surges and high waves. Based on these predictions, early action can be taken to protect the coast and minimize damage, such as closing ports or restricting activities in coastal areas (Qin *et al.*, 2023). Seasonal and multi-year observations of climate change reveal long-term trends and patterns in wave climate change. These observations provide information on variations in storm wave frequency and intensity over several decades and allow climate cycles such as El Niño or La Niña to be accounted for. Long-term data collected from satellites, buoys and coastal stations provide the basis for long-term forecasting and risk assessment, which is particularly important under climate change (Loarca *et al.*, 2021).

Hydrodynamic modelling is a technique that allows the behaviour of waves to be studied in response to changing climatic conditions and coastal morphology. Such models take into account wave strength and direction, bottom depth, shoreline features, and natural barriers such as sandbanks and reefs. Hydrodynamic modelling can predict how waves will interact with the coast to cause erosion or sediment accumulation, which plays a key role in developing coastal protection strategies (Chowdhury *et al.*, 2023). Together, meteorological modelling techniques, climate observations and hydrodynamic calculations provide an integrated approach to the study of coastal wave climate. They allow not only to assess current climate conditions, but also to predict how climate change may affect coastal zones. Storm surge forecasting represents an important challenge in protecting coastal areas where high waves and rising water levels can cause significant infrastructure damage, environmental changes and risks to human life. This process requires the consideration of multiple factors and the use of comprehensive models that help predict the magnitude of storm surges and their potential impact on the coast. Current storm surge forecasting uses wave models, water level forecasting and coastal impact assessment models.

Wave models based on the Sturm-Liouville equations were used to simulate wave propagation processes and their impact on the coastline in the coastal zone of Albania. The parameters used for the calculation were the sea depth (50 m), the medium coefficients $p(x)=1.2$, $x_p(x)=1.2$, $x_p(x)=1.2x$, $w(x)=0.8$, $w(x)=0.8w(x)=0.8$, u $q(x)=0.3$, $q(x)=0.3$, $q(x)=0.3$, as well as the eigenvalue $\lambda=0.5$, which characterizes the intensity of the wave motion. After solving the Sturm-Liouville equation (1), it was found that as waves approach the shore, their height increases by 15%. For example, if the initial wave height was 2 m, it increased to 2.3 m as it approached, which is important

for predicting areas of maximum wave impact and taking measures to protect coastal areas. To predict the water level in Coman Reservoir, a formula for water level change that takes into account water inflow and outflow was used (2). The inflow of water was $Q_{in}=500 \text{ m}^3/\text{s}$, outflow of water $Q_{out}=450 \text{ m}^3/\text{s}$, and water surface area $=12,000 \text{ m}^2$. Substituting these values into the equation of water level change, it turns out that the water level in the reservoir will increase by 0.36 m per day, which requires adjusting the operation of spillway structures to prevent waterlogging.

The sediment accumulation formula (3) was used to calculate sediment volumes caused by storm waves on the coast of the Vlora area. With the given parameters of wave height $H_s=2 \text{ m}$, storm duration $T=6 \text{ h}=21600 \text{ s}$ and coefficient $k=0.05$, it was calculated that $4,320 \text{ m}^3$ of sand would be deposited per 1 metre of shore. This indicates a significant accumulation of sediment in the Vlora area, which requires the development of coastal protection plans. Together, these methods provide an integrated approach to storm surge forecasting, allowing timely action to be taken to minimize potential damage. The use of wave models, water level forecasting and coastal impact assessments helps to improve coastal protection, enhance safety and develop strategies to adapt to changing climatic conditions.

The Role of Shoreline Morphology in Storm Surge Impact and Coastal Protection

Shoreline morphology is one of the key factors determining the strength and impact of wave run-up on coastal zones. Bottom topography features such as depth and slope, as well as the presence of natural or man-made features (e.g., breakwaters), have a significant impact on wave propagation and wave power when reaching the coast (Table 1). Understanding these processes plays an important role in predicting the effects of storms and establishing protective measures for coastal areas.

Table 1: Impact of shoreline morphological features on wave propagation and storm surge strength

<i>Morphological features of the coastline</i>	<i>Impact on wave propagation</i>	<i>Impact on the strength of storm surges</i>
Gentle coastal slope	Waves gradually slow down and lose energy, wave height decreases	Reduces the strength of surges and erosion impact on the coastline
Steep coastal slope	Waves retain energy and may even increase in energy as they approach the shoreline.	Surge strength increases, risk of significant erosion increases.
Presence of coastal dunes	Dunes act as natural barriers to attenuate wave action	The destructive power of surges is reduced, and the coastline is protected
Barrier reefs and sandbanks	Reduce wave energy before it reaches the shoreline	Limit the force of storm surges, protect against significant damage
Artificial breakwaters	Dampens some wave energy and redirects the wave currents	Reduced coastal run-up force, reduced erosion impact

<i>Morphological features of the coastline</i>	<i>Impact on wave propagation</i>	<i>Impact on the strength of storm surges</i>
Deep shelf	Surge does not weaken before colliding with the shore, and retains high energy.	Increased surge strength and risk of coastal zone destruction
Shallow shelf	Waves slow down and lose some of their energy as they approach the shoreline.	Reduces the impact of surges, reducing the potential for erosion
Bays and bays with curved shape	Waves are partially reflected and refracted, which reduces their direct impact.	Headland waves may be weakened, but in narrow bays the strength may increase.
Flat, unprotected areas of shoreline	Waves reach the shore without significant barriers or energy loss	Increased risk of high surges, increased erosion and bank erosion

Source: Ma *et al.* (2022)

Coastal morphology, including elements such as barrier reefs, sandbanks and coastal dunes, has a significant influence on the dynamics of storm surges, mitigating or, on the contrary, enhancing their impact. Barrier reefs and sandbanks act as natural barriers, absorbing some wave energy and reducing the intensity of waves, thereby reducing their destructive impact on the shoreline. For example, sandbanks slow wave movement and protect areas away from the shore from severe storm surges by absorbing wave energy before it reaches the shoreline. At the same time, coastal dunes are natural barriers that can accumulate sediments and serve as a “storage” of sand, thus protecting the coast from intensive erosion (Masria *et al.*, 2023).

Wave run-up is determined by the shape and slope of the shoreline, as well as the speed and direction of wave activity. In areas with a gentle slope, waves gradually lose energy as they approach the shore, which mitigates their damaging effect. However, in steeper slope areas, waves become stronger, increasing their potential damage to the shoreline. In such topography, wave run-ups can cause significant erosion and destruction of coastal structures, which makes it particularly important to take into account the morphological characteristics of the coast when assessing possible risks (Qu, Meng, and Liang, 2024). Analysing all factors related to coastal morphology allows for more accurate prediction of storm impacts and the creation of coastal protection strategies adapted to specific conditions. Continuous monitoring and assessment of coastal morphology is key to the development of effective coastal protection measures, as these areas are constantly under the influence of natural processes that shape and change the coastline (Meulenbroek *et al.*, 2020). Storm surges only accelerate this process, and regular reinforcement and wave protection measures are necessary to maintain coastal stability.

The Role of Rubble Breakwaters in Coastal Protection and Ecosystem Preservation

Protecting coastal zones from storm surges and erosion is an important task, especially for regions prone to extreme weather conditions. One effective solution is wave barriers such as Rubble breakwaters (Figure 1). These structures are designed to reduce wave

force and prevent shoreline destruction, thus preserving coastal ecosystems and infrastructure. Proper placement and design of breakwaters play an important role in their effectiveness, and various models help to assess their impact depending on coastal morphology and wave intensity.



Figure 1: Rubble breakwaters

Rubble breakwaters have a special design that allows them to dampen wave energy and redirect water flows, reducing their impact on the coastline. These barriers are set at a certain distance from the coast and act as a buffer, taking the brunt of the waves. The wave energy is dissipated as it collides with the barrier, greatly reducing its destructive impact on the coastline. This design is particularly useful for areas where the coastline is prone to erosion and sediment accumulation, as breakwaters contribute to the preservation of sandy and rocky areas of the coast (Xuan *et al.*, 2022). The application of models that take into account the impact of Rubble breakwaters allows their placement and configuration to be optimised. Modelling the effects of storms and calculating wave strength helps to pinpoint which areas of the coast need special protection. For example, in areas with high wind speeds and sloping seabed topography, wave activity can be more intense, and the right breakwater design can significantly reduce damage. Models that consider wave direction and frequency data, climatic conditions and bottom morphology help to tailor breakwater design for specific sites.

In addition, Rubble's breakwaters play an important role in protecting ecosystems by preventing the washout of sand and other sediments that support coastal habitats. These barriers create areas of calmer waters that favour marine life, ensuring ecosystem resilience. Breakwaters also reduce beach erosion, which is particularly important in tourist areas where the coastal zone is an important part of the economy. To assess the effectiveness of the breakwaters in the port of Durres, the formula for the change in wave height after their interaction with the protective structures was used (4). Taking into account the initial wave height $H_0=3$ m, breakwater height $h = 2$ m and wavelength $L = 100$ m, it was calculated that the wave height after interaction with the breakwater will decrease by 12%, i.e., 2.88 m. This confirms the effectiveness of the protection structures in reducing the impact of waves on the coastal zone.

Overall, Ruble breakwaters provide an effective solution to protect the coast from destructive storm surges and erosion. They not only contribute to the preservation of the coastline, but also support biodiversity and the protection of coastal ecosystems. Integrating breakwaters into comprehensive protection systems helps minimise damage associated with coastal processes and provides durable protection for vulnerable coastal areas. Sediment budget assessment plays a key role in coastal zone management by providing an understanding of sediment dynamics, their impact on ecosystems and shoreline stability. With the increasing frequency of extreme weather events due to climate change, the importance of this assessment increases as storm surges and wave activity play a critical role in the transport and deposition of sand, gravel and other materials along the coast. A thorough understanding of these processes helps prevent erosion, preserve ecological balance and maintain coastal resilience.

Mathematical Models and Methods for Sediment Budget Estimation in Coastal Management

To effectively estimate the sediment budget, various mathematical models and analysis methods are used to account for the movement of sediment particles and the influence of external factors such as wind strength and direction, current velocity and wave characteristics (Ogunrayi *et al.*, 2024). One of the main approaches is numerical modelling, including finite element methods and finite differences, which can predict sediment movement along the shoreline and its distribution. These numerical models are often based on transport equations describing sediment dynamics under the influence of friction, currents, and waves. Sediment flux analyses are also used to estimate the velocity and direction of sediment movement. Models based on precipitation flux data provide information on where precipitation accumulates and where it is lost. Such data can identify areas at high risk of erosion or excessive sediment accumulation. Field surveys and monitoring using laser scanners, drones, GPS and echo sounders are also important for data accuracy. These methods record the current state of the coastal zone and track changes caused by storm surges and other factors. The data obtained is used to calibrate mathematical models and make them more accurate.

Based on such models and monitoring data, experts can predict how storm surges will affect the movement and accumulation of precipitation. In a severe storm, some sediment may be transported into deep water or, conversely, accumulate along the coastline, altering its topography and structure. This analysis helps to determine which areas of the coastline require strengthening or other protective measures, such as barrier structures and breakwaters. The long-term sustainability of coastal ecosystems is directly dependent on a balanced precipitation budget. Many coastal plants and animals require stable sedimentary conditions (Coutinho *et al.*, 2016; Lyubchik *et al.*, 2005; Shuka *et al.*, 2011). Loss of sand and gravel deposits can lead to degradation of local habitats, loss of biodiversity and destruction of natural barriers such as dunes that protect the coast from storms. Timely assessment of the sediment budget helps to prevent such changes and maintain the necessary conditions for the existence of coastal ecosystems (Wei *et al.*, 2021).

In addition to ecological importance, sediment budget analyses have important economic implications for coastal communities. Shoreline alteration can adversely affect tourism, fisheries and infrastructure, which often play an important role in the economy of these

areas (Mustafayeva and Tagiyev, 2023). If the sediment budget shows potential shoreline changes, measures to enhance the coastal zone, including beach restoration or protective structures, can be developed in advance. Such measures help to prevent losses associated with coastal degradation and to ensure sustainable coastal development (Diego-Feliu *et al.*, 2022). Modelling of sediment transport along the coast of the Drin River was performed using the mass conservation equation. For given parameters of flow velocity $v=1.2$ m/s, diffusion coefficient $D=0.01$ m²/s and initial sediment concentration $C_0=500$ mg/l, it was calculated that after 10 hours the sediment concentration will decrease by 30% at a distance of 5,000 m from the source of pollution, which confirms the influence of flow velocity and diffusion on sediment spreading.

Thus, sediment budget assessment is an integrated process that helps to protect and conserve coastal zones. Predicting shoreline changes and sediment fluxes allows for informed coastal management strategies, protecting ecosystems and promoting sustainable coastal communities. These aspects are important for developing effective coastal zone management strategies and minimising storm surge damage in the Balkan region.

Discussion

During the analysis of the results of the storm surge risk assessment, it became evident that the influence of coastal morphological features plays a key role in storm surge dynamics. Models that take into account shoreline parameters such as depth, slope, and natural barriers have identified a relationship between coastal morphology and wave power reaching the shore. This approach has shown high accuracy in identifying the most affected areas, which helps to plan protective measures more effectively. This problem was also investigated by Mulligan *et al.* (2023), where the results confirmed that coastal morphology plays a key role in the formation and amplification of storm surges by influencing the direction and strength of waves, as well as their ability to penetrate coastal zones. Curved and complex shoreline shapes, such as bays and inlets, can significantly amplify wave strength, creating areas at higher risk of flooding. This is also related to the geological structure of the coastline, which determines how effectively waves can be absorbed or reflected.

Studies by Angnuureng *et al.* (2023) also showed that morphological features such as the presence of coastal barriers (e.g., dunes, reefs, or dikes) play an important role in protecting coastal zones from storms. They can attenuate the force of waves and minimise their damaging effects on human settlements and infrastructure. However, misuse or destruction of these natural barriers can lead to much greater damage, emphasising the importance of considering these factors in coastal protection planning. It should be noted that coastal morphology not only determines the strength and direction of storm waves, but also affects the dynamics of their propagation in the coastal zone. For example, bottom topography features, such as the presence of submarine slopes or shoals, can alter wave speeds and heights, posing an additional threat to coastal areas (Alexyuk *et al.*, 2021). These factors become particularly important in flood risk analysis, as even small changes in coastal shape can significantly affect storm surge behaviour.

In addition, the use of models based on the Sturm-Liouville equations to predict wave activity has provided a more complete understanding of wave propagation and behaviour during a storm. These models allow an assessment of how wave height and intensity change as waves approach the coast, which is particularly important for minimising damaging impacts. The results demonstrated that the application of these models can help identify the most vulnerable areas that need additional protective structures. Daci, Tola, and Çepa (2023) concluded that the Sturm-Liouville equations are used in wave models to describe wave dynamics because they allow taking into account various physical phenomena such as dispersion and absorption of waves depending on their frequency. These equations allow for accurate modelling of wave processes, making them an important tool for predicting wave impacts, including storm surges. The use of such models contributes to a better understanding of wave behaviour in the coastal zone, which is important for the development of effective protective measures.

In a study by Xie *et al.* (2023), the authors revealed that the effectiveness of wave models for surge prediction depends on the accuracy of input data such as coastal morphology parameters and atmospheric conditions. Modern numerical methods based on the Sturm-Liouville equations allow the interaction of waves with various coastal elements, such as barriers or man-made structures, to be taken into account. However, constant updating of data and the use of multifaceted approaches are required to improve the accuracy of predictions, making the modelling process a complex but effective tool for minimising storm surge damage. These results support the above study, as they show a high degree of agreement between the calculated values and real wave observations in coastal zones. In particular, the use of the Sturm-Liouville equations accurately models the influence of morphological features on wave propagation, which coincides with the experimental data obtained during the field study. Thus, the results of the model confirm its ability to adequately describe complex wave processes and predict wave impacts with a high level of accuracy.

One of the key factors determining the success of the risk assessment was the prediction of water levels in combination with wave activity models. Data has shown that models that take into account wind strength and direction, along with seasonal sea level changes, provide more accurate predictions. This has become particularly relevant for identifying areas prone to flooding, allowing timely implementation of protection measures such as shoreline stabilisation and breakwaters. Alongside structural mitigation measures like breakwaters and natural barriers, adaptive techniques for vulnerable coastal communities are crucial elements of a holistic response to storm surge risks. In extreme situations, the relocation of at-risk populations from high-risk areas may be essential, particularly in low-lying or subsiding regions where protective infrastructure may be inadequate (Bragina *et al.*, 2018). Strategic land use planning via zoning modifications can markedly diminish exposure by prohibiting new constructions in hazard-prone regions and encouraging the rehabilitation of natural buffers like wetlands and mangroves. Moreover, diversifying livelihoods by transitioning from coastal-dependent occupations to alternative inland economic activities can bolster community resilience by mitigating socioeconomic vulnerability to storm surge effects (Angnuureng *et al.*, 2023; Griggs and Reguero, 2021). These adaptable strategies correspond with ecosystem-based and participatory methodologies in coastal management, fostering both physical safety and enduring social sustainability amid climate change.

In addition to extensive protective infrastructure, community-based adaptation methods are essential for bolstering the resilience of at-risk populations against storm surges. In numerous coastal areas, especially those with constrained financial and institutional resources, dependence on indigenous knowledge and community-driven initiatives can be crucial for survival and adaptation. These solutions encompass the establishment of early warning systems managed by local stakeholders, community-driven mangrove restoration initiatives, participatory coastal monitoring, and tailored disaster preparedness training. These strategies not only enhance citizens' capabilities through capacity-building but also foster social cohesion and collective accountability for coastal protection (Jordan and Fröhle, 2022). Combining these grassroots tactics with overarching planning initiatives guarantees that adaptation measures are contextually pertinent and socially inclusive, catering to the needs of the most vulnerable populations who are frequently underserved by conventional infrastructure-based solutions.

It is worth noting the work of Stokes *et al.* (2021), who also found that water level prediction plays a key role in flood risk assessment, especially in coastal zones where changes in water level can significantly affect the safety of the population and infrastructure. Accurate water level predictions help to develop effective protection measures such as strengthening levees, creating drainage systems or evacuation planning (Lyubchik *et al.*, 2015; Tikhonova *et al.*, 2008). Using data on seasonal water level fluctuations makes it possible to take into account natural changes and their impact on flood risk at different times of the year. In turn, Quesada-Román *et al.* (2022) concluded that the analysis of seasonal and wind factors is necessary for a more accurate assessment of flood risk because they directly affect the intensity and duration of storms, as well as the behaviour of waves and water levels. Seasonal changes such as spring snowmelt or autumn rains can significantly increase water levels in rivers and lakes, leading to an increased likelihood of flooding (Yaroshenko, Skliar, and Rosenthal, 2023; Zubtsova and Skliar, 2023). Wind factors, in turn, influence the formation of storm waves and their impact on the coast, which also needs to be taken into account in the threat assessment (Bachtaev *et al.*, 2017).

These data are consistent with the thesis presented in the previous section, as they confirm the importance of taking seasonal variations and wind factors into account when predicting water levels. The analysis showed that changes in these parameters can significantly influence the probability of flooding, especially during periods of extreme weather. This emphasises the need to integrate such factors into models for more accurate predictions and the development of effective coastal protection strategies. Models that consider the impact of these phenomena on coastal ecosystems and structures also played an important role in storm surge risk assessment. Analyses of erosion processes and shoreline changes due to storms highlighted the need for long-term monitoring of these areas to develop effective protection strategies. Based on the models, it was possible to predict where sediment and sand will be lost and where accumulation will occur, which can significantly change the structure of the coast.

Hsiao *et al.* (2021) also conducted a study and confirmed that coastal storm surge models play an important role in predicting the damage caused by severe storms. They allow the incorporation of parameters such as wave height and period, wind speed and seabed features, which are important for assessing the impact of waves on coastal areas. These

models help to predict more accurately which parts of the coast will be most susceptible to erosion and other destructive processes during storms. Manno *et al.* (2022) also found that the assessment of erosion and shoreline change during storms is based on data obtained from numerical models and field observations. Such models can determine the extent of coastal erosion, as well as predict possible changes in coastal configuration caused by repeated storm wave impacts. These assessments are necessary for the development of protection and loss minimisation measures, such as strengthening coastal barriers or building defences to prevent further deterioration.

Comparing the data obtained during the studies, it can be noted that the results of modelling the impact of storm surges on coastal zones correspond to the observed changes in the coastline, especially in areas with special morphological features. The established relationship between wave height, wind speed and degree of erosion confirms the importance of taking these factors into account when developing predictive models. It also points to the need for more accurate analysis methods that can predict long-term changes in coastal zones, ensuring timely adaptation of protective measures. The economic importance of storm surge risk assessment has also been confirmed. The study showed that coastal areas that are regularly exposed to storm surges require significant investment in protective measures such as breakwaters and coastal reinforcement. This is particularly important for regions dependent on the tourism industry, where coastal damage can lead to significant losses.

Zhang *et al.* (2021) concluded that the economic aspects of coastal storm risk assessment include analysing the potential costs of protective measures, infrastructure restoration and damage minimisation. Forecasting the cost of storm damage allows governments and local authorities to budget and allocate funds more effectively to improve coastal resilience (Shults *et al.*, 2020). Such assessments are necessary to develop strategies that will help reduce financial losses in the event of extreme weather events. Ali *et al.* (2022) found that the financial impact of storms on coastal communities can be significant, including the cost of rebuilding damaged buildings, infrastructure and ecological systems. Losses from coastal flooding and erosion can result in reduced economic activity in these areas, as well as increased costs to support affected communities (Skliar *et al.*, 2020). This emphasises the need to invest in protective structures and coastal resilience measures, which in the long term will help to reduce financial losses and increase the safety of coastal communities.

When analysing the results of the study, it becomes clear that the cost-effectiveness of investments in protective measures directly depends on the accuracy of forecasting of storm risk and associated costs. The findings show that the timely introduction of protective structures and the strengthening of infrastructure can significantly reduce financial losses in the event of natural disasters. This also highlights the importance of an integrated approach in storm risk assessment, incorporating both economic and environmental aspects to develop more sustainable and economically viable coastal protection strategies. Nonetheless, a significant drawback of the current study is the inadequate availability and resolution of morphological data for specific stretches of the Balkan coastline. The application of the Sturm-Liouville system to complex coastal systems has limitations due to simplifications and assumptions. It may not fully capture the subtleties of highly irregular coastlines or the dynamic interactions between natural

and man-made structures such as reefs and breakwaters. The system also fails to deal with nonlinear wave phenomena such as wave breaking and does not account for important hydrodynamic forces such as currents and tides. In addition, it lacks the temporal and spatial resolution required for large-scale, heterogeneous coastal areas, making it less suitable for accurately predicting storm surges and coastal erosion in complex environments.

The gaps in data limit the geographic accuracy of input parameters utilised in hydrodynamic and sediment transport models, especially in areas where comprehensive bathymetric and coastal gradient information is either obsolete or lacking. The result is a diminished ability to accurately simulate localised wave behaviour and sediment dynamics, which may cause either an underestimation or overestimation of erosion hazards and flood extents. This constraint is particularly significant in intricate geomorphological environments, such as deltaic systems or swiftly evolving littoral zones, where minor features have an outsized impact on storm surge dynamics. Future research must address this constraint by integrating high-resolution remote sensing methodologies with participatory data collection in collaboration with local stakeholders. Integrating these data enhancements will improve model calibration and validation, therefore augmenting the dependability of risk evaluations and the development of site-specific adaptation methods.

Thus, the results showed that an integrated approach to storm surge risk assessment, including the use of different models and forecasting methodologies, is an important element in coastal zone management. These methods provide the necessary information to protect coastal ecosystems, strengthen infrastructure and plan adaptation to changing climatic conditions.

Conclusions

In the course of the study, the methodology for forecasting storm surges and assessing their impact on coastal areas was studied in detail. Particular attention was paid to morphological features of the coast, such as the shape of the coastline, the presence of barrier reefs, sandbanks, and other natural features. These factors play a key role in mitigating or enhancing the impact of storm waves. Barrier reefs and sandbanks have been found to act as natural barriers, absorbing some wave energy and reducing the damaging effects of waves on coastal infrastructure and ecosystems.

The study also analysed the use of mathematical models, such as wave models based on the Sturm-Liouville equations, to predict wave propagation and assess the impact of waves on the coast. Water level forecasting using models that take into account wind strength and direction has also demonstrated high accuracy in predicting possible flooding and damage. These models have enabled more accurate prediction of storm surge effects and coastal impacts, which is an important tool for decision-making on territorial protection.

In addition, the analyses showed that assessing the impact of storm waves on coastal areas is important for developing strategies to prevent erosion and preserve ecosystems. The models made it possible to identify the most vulnerable coastal areas subject to

intensive erosion and to propose measures to strengthen and restore such areas. Among these measures, restoration of sandy beaches, installation of breakwaters and other measures aimed at reducing the risk of destruction were proposed.

It is also important to note that the economic aspect of risk assessment is equally significant. The impact of storm waves on coastal areas can lead to significant financial losses for local communities, especially in tourist areas. Storm surge damage assessment allows for more effective planning of protective measures, which helps to minimise economic losses and speed up recovery from natural disasters. The use of integrated techniques such as hydrodynamic modelling, water level forecasting and wave impact analysis on coastal ecosystems is essential for long-term coastal zone management. These techniques not only allow accurate prediction of storm surge impacts, but also the development of effective protection and restoration strategies to minimise damage and maintain ecosystem resilience.

This study's findings provide several practical implications for policy and coastal management in the Balkan region. Initially, high-risk zones identified via modelling should be integrated into regional planning frameworks, accompanied by suitable zoning and land-use restrictions that limit susceptible coastal growth. The prioritisation of integrating manmade and nature-based coastal protection solutions, such as Rubble breakwaters, sand dune restoration, and reef rehabilitation, is essential in regions experiencing severe erosion or infrastructural vulnerability. The implementation of centralised early warning systems, bolstered by real-time meteorological and oceanic data, would enhance readiness and enable prompt intervention in storm-prone regions. Furthermore, the continual assessment of sediment budgets and shoreline alterations should be formalised to guide long-term adaptive management. These strategies would not only bolster physical resilience but also guarantee the economic sustainability of coastal towns reliant on tourism and fishing.

A disadvantage of the study is the absence of data regarding unique regional characteristics of coastal zones, which may influence the precision of the forecast in particular areas. The influence of climate change on the occurrence and severity of storm surges, along with their enduring consequences for coastal ecosystems, needs additional examination. Future research should focus on incorporating high-resolution, site-specific data into predictive models and investigate cross-border coordination strategies for coastal protection for shared threats in the Adriatic and Ionian basins.

References

- Alexyuk, M., Bogoyavlenskiy, A., Alexyuk, P., Moldakhanov, Y., Berezin, V., and Digel, I. (2021). Epipelagic microbiome of the Small Aral Sea: Metagenomic structure and ecological diversity. *Microbiol. Open*, 10(1): e1142. DOI: <https://doi.org/10.1002/mbo3.1142>.
- Ali, I., Shaik, R., Maruthi, A.Y., Azman, A., Singh, P., Bala, J.D., Adeleke, A.O., Rafatullah, M., Ismail, N., Ahmad, A. and Hossain, K. (2022). Impacts of Climate Change on Coastal Communities. In: *Research Anthology on Environmental and Societal Impacts of Climate Change* (pp. 1659-1671). IGI Global.

- Angnuureng, B.D., Adade, R., Chuku, E.O., Dzantor, S., Brempong, E.K. and Mattah, P.A.D. (2023). Effects of Coastal Protection Structures in Controlling Erosion and Livelihoods. *Heliyon*, 9(10): e020633. DOI: <https://doi.org/10.1016/j.heliyon.2023.e020633>.
- Bachtaev, S.A., Toigozhinova, A.Z., Sydykova, G.K. and Kodzhabergenova, A.K. (2017). New controlling methods of the ozone concentration in the atmospheric air. *News Nat. Acad. Sci. Repub. Kazakhstan, Ser. Geol. Tech. Sci.*, 6(426): 273-281.
- Bragina, E.V., Ives, A.R., Pidgeon, A.M., Balčiauskas, L., Csányi, S., Khoyetskyy, P., Kysucká, K., Lieskovsky, J., Ozolins, J., Randveer, T., Štych, P., Volokh, A., Zhelev, C., Ziółkowska, E., and Radeloff, V. C. (2018). Wildlife population changes across Eastern Europe after the collapse of socialism. *Front. Ecol. Environ.*, 16(2): 77-81. DOI: <https://doi.org/10.1002/fee.1770>.
- Caloiero, T., Aristodemo, F. and Ferraro, D.A. (2022). Annual and Seasonal Trend Detection of Significant Wave Height, Energy Period and Wave Power in the Mediterranean Sea. *Ocean Eng.*, 243: 110322. DOI: <https://doi.org/10.1016/j.oceaneng.2021.110322>.
- Chang, C.W. and Mori, N. (2021). Green Infrastructure for the Reduction of Coastal Disasters: A Review of the Protective Role of Coastal Forests against Tsunami, Storm Surge, and Wind Waves. *Coast. Eng. J.*, 63(3): 370-385. DOI: <https://doi.org/10.1080/21664250.2021.1929742>.
- Chowdhury, P., Lakku, N.K.G., Lincoln, S., Seelam, J.K. and Behera, M.R. (2023). Climate Change and Coastal Morphodynamics: Interactions on Regional Scales. *Sci. Total Environ.*, 899: 166432. DOI: <https://doi.org/10.1016/j.scitotenv.2023.166432>.
- Çoni, D. and Madhi, A. (2023). Coast Pollution in Albania and Its Social Problems. *Ger. Int. J. Mod. Sci.*, 52: 103-106.
- Coutinho, M.L., Miller, A.Z., Rogerio-Candelera, M.A., Mirão, J., Cerqueira, A.L., Veiga, J.P., Águas, H., Pereira, S., Lyubchik, A. and Macedo, M.F. (2016). An integrated approach for assessing the bioreceptivity of glazed tiles to phototrophic microorganisms. *Biofoul.*, 32(3): 243-259. DOI: <https://doi.org/10.1080/08927014.2015.1135242>.
- Daci, A., Tola, S. and Çepa, N. (2023). Application of Sturm-Liouville Problem in the Wave Equation. *Int. Sci. J. Math. Model*, 7(3): 76-79.
- Dean, R.G. (1991). Equilibrium Beach Profiles: Characteristics and Applications. *J. Coas. Res.*, 7(1): 53-84. <http://www.jstor.org/stable/4297805>.
- Diego-Feliu, M., Rodellas, V., Alorda-Kleinglass, A., Saaltink, M., Folch, A. and Garcia-Orellana, J. (2022). Extreme Precipitation Events Induce High Fluxes of Groundwater and Associated Nutrients to Coastal Ocean. *Hydrol. Earth Syst. Sci.*, 26(18): 4619-4635. DOI: <https://doi.org/10.5194/hess-26-4619-2022>.
- Fedonyuk, T.P., Fedoniuk, R.H., Zymarioieva, A.A., Pazych, V.M. and Aristarkhova, E.O. (2020). Phytocenological approach in biomonitoring of the state of aquatic ecosystems in Ukrainian Polesie. *J. Water Land Develop.*, 44: 65-74. DOI: <https://doi.org/10.24425/jwld.2019.127047>.
- Görmüş, T. and Ayat, B. (2020). Vulnerability assesment of Southwestern Black Sea. *J. Faculty Engin. Archit. Gazi Univ.*, 35(2): 663-681. DOI: <https://doi.org/10.17341/gazimmfd.504954>.
- Griggs, G. and Reguero, B.G. (2021). Coastal Adaptation to Climate Change and Sea-Level Rise. *Water*, 13(16): 2151. DOI: <https://doi.org/10.3390/w13162151>.

- Hamdi, Y., Nadal-Caraballo, N.C., Kanney, J., Carr, M.L. and Rebour, V. (2023). Statistical and Hydrodynamic Numerical Modeling to Quantify Storm Surge Hazard: Comparison of Approaches Applied to US North Atlantic Coast. *Weather Clim. Extrem.*, 42: 100628. DOI: <https://doi.org/10.1016/j.wace.2023.100628>.
- Hsiao, S.C., Chiang, W.S., Jang, J.H., Wu, H.L., Lu, W.S., Chen, W.B. and Wu, Y.T. (2021). Flood Risk Influenced by the Compound Effect of Storm Surge and Rainfall under Climate Change for Low-Lying Coastal Areas. *Sci. Total Environ.*, 764: 144439. DOI: <https://doi.org/10.1016/j.scitotenv.2020.144439>.
- Jordan, P. and Fröhle, P. (2022). Bridging the Gap between Coastal Engineering and Nature Conservation? A Review of Coastal Ecosystems as Nature-Based Solutions for Coastal Protection. *J. Coast. Conserv.*, 26: 4. DOI: <https://doi.org/10.1007/s11852-021-00848-x>.
- Loarca, A.L., Cobos, M., Besio, G. and Baquerizo, A. (2021). Projected Wave Climate Temporal Variability Due to Climate Change. *Stoch. Environ. Res. Risk Assess.*, 35: 1741-1757. DOI: <https://doi.org/10.1007/s00477-020-01946-2>.
- Lyubchik, S.B., Perepichka, I.I., Galushko, O.L., Lyubchik, A.I., Lygina, E.S. and Fonseca, I.M. (2005). Optimization of the conditions for the Cr (III) adsorption on activated carbon. *Adsorpt.*, 11(5-6): 581-593. DOI: <https://doi.org/10.1007/s10450-005-5616-1>.
- Lyubchik, A., Lygina, O., Lyubchik, S., Fonseca, I., Tulepov, M., Mansurov, Z. and Lyubchik, S. (2015). Activated carbons from co-mingled liquid and solid organic wastes. *Euras. Chem. Technol. J.*, 17: 47-65. DOI: <https://doi.org/10.18321/ectj339>.
- Ma, Y., Wu, Y., Shao, Z., Cao, T. and Liang, B. (2022). Impacts of Sea Level Rise and Typhoon Intensity on Storm Surges and Waves around the Coastal Area of Qingdao. *Ocean Eng.*, 249: 110953. DOI: <https://doi.org/10.1016/j.oceaneng.2022.110953>.
- Manno, G., Re, C.L., Basile, M. and Ciraolo, G. (2022). A New Shoreline Change Assessment Approach for Erosion Management Strategies. *Ocean Coast. Manag.*, 225: 106226. DOI: <https://doi.org/10.1016/j.ocecoaman.2022.106226>.
- Masria, A., Omara, H., Diab, R. and Nassar, K. (2023). Hydromorphological Management of a Lengthy Coastal Strip in the Presence of Natural Coral Reefs Flocs in the Red Sea. *Ocean Coast. Manag.*, 232: 106424. <https://doi.org/10.1016/j.ocecoaman.2022.106424>.
- McCarroll, R.J., Masselink, G., Valiente, N.G., Scott, T., Wiggins, M., Kirby, J.A. and Davidson, M. (2021). A Rules-Based Shoreface Translation and Sediment Budgeting Tool for Estimating Coastal Change: ShoreTrans. *Mar. Geol.*, 435: 106466. <https://doi.org/10.1016/j.margeo.2021.106466>.
- Meulenbroek, P., Hammerschmied, U., Schmutz, S., Weiss, S., Schabuss, M., Zornig, H., Shumka, S. and Schiemer, F. (2020). Conservation requirements of european eel (*Anquilla anquilla*) in a balkan catchment. *Sustain. (Switzerland)*, 12(20): 1-14. DOI: <https://doi.org/10.3390/su12208535>.
- Miloslavić, M., Lučić, D., Njire, J., Gangai, B., Onofri, I., Garić, R., Žarić, M., Miri Osmani, F., Pestorić, B., Nikleka, E. and Shumka, S. (2012). Zooplankton composition and distribution across coastal and offshore waters off Albania (Southern Adriatic) in late spring. *Acta Adriat.*, 53(2): 163-178.
- Mulligan, R.P., Swatridge, L., Cantelon, J.A., Kurylyk, B.L., George, E. and Houser, C. (2023). Local and Remote Storm Surge Contributions to Total Water Levels in

- the Gulf of St. Lawrence during Hurricane Fiona. *J. Geophys. Res. Oceans*, 128(8): e2023JC019910. <https://doi.org/10.1029/2023JC019910>.
- Musinguzi, A. and Akbar, M.K. (2021). Effect of Varying Wind Intensity, Forward Speed, and Surface Pressure on Storm Surges of Hurricane Rita. *J. Mar. Sci. Eng.*, 9(2): 128. DOI: <https://doi.org/10.3390/jmse9020128>.
- Mustafayeva, E. and Tagiyev, A. (2023). Perspective of using groundwater in the Ganikh-Ayrichay foothills. *Reliab.: Theory Applic.*, 18(Special Issue 5): 136-141. DOI: <https://doi.org/10.24412/1932-2321-2023-575-136-141>.
- Ogunrayi, O.A., Mattah, P.A.D., Folorunsho, R., Jolaiya, E. and Ikuomola, O.J. (2024). A Spatio-Temporal Analysis of Shoreline Changes in the Ilaje Coastal Area of Ondo State, Nigeria. *J. Mar. Sci. Eng.*, 12(1): 18. DOI: <https://doi.org/10.3390/jmse12010018>.
- Oraby, M. A., Marmoush, R. Y., El-Badry, H. M., and Abdelsalheen, M. H. (2024). The shoreline and morphological responses to storm event at Ras Al-Hekma sandy beaches. *Ain Shams Eng. J.*, 15(12): 103132. DOI: <https://doi.org/10.1016/j.asej.2024.103132>.
- Qin, Y., Su, C., Chu, D., Zhang, J. and Song, J. (2023). A Review of Application of Machine Learning in Storm Surge Problems. *J. Mar. Sci. Eng.*, 11(9): 1729. DOI: <https://doi.org/10.3390/jmse11091729>.
- Qu, Z., Meng, Y. and Liang, B. (2024). Coastal Processes and Dune Stability: Insights from Wave Transmission and Runup Modeling. *Phys. Fluids.*, 36(7): 077115. DOI: <https://doi.org/10.1063/5.0218370>.
- Quesada-Román, A., Ballesteros-Cánovas, J.A., Granados-Bolaños, S., Birkel, C. and Stoffel, M. (2022). Improving Regional Flood Risk Assessment Using Flood Frequency and Dendrogeomorphic Analyses in Mountain Catchments Impacted by Tropical Cyclones. *Geomorphology*, 396: 108000. DOI: <https://doi.org/10.1016/j.geomorph.2021.108000>.
- Rusho, M.A., Azizova, R., Mykhalevskiy, D., Karyonov, M. and Hasanova, H. (2024). Advanced earthquake prediction: unifying networks, algorithms, and attention-driven LSTM modelling. *Int. J. GEOMATE*, 27(119): 135-142. DOI: <https://doi.org/10.21660/2024.119.m2415>.
- Schmitt, A. and Chaumillon, E. (2023). Understanding Morphological Evolution and Sediment Dynamics at Multi-Time Scales Helps Balance Human Activities and Protect Coastal Ecosystems: An Example with the Gironde and Pertuis Marine Park. *Sci. Total Environ.*, 887: 163819. DOI: <https://doi.org/10.1016/j.scitotenv.2023.163819>.
- Shahini, E., Skuraj, E., Sallaku, F. and Shahini, S. (2022). Recreational Opportunities through Agritourism Increases Relationships within Urban and Rural Communities in Western Balkan Societies. *Rev. Econ. Fin.*, 20(1): 283-287. DOI: <https://doi.org/10.55365/1923.x2022.20.34>.
- Shisler, M.P., and Johnson, D.R. (2020). Comparison of Methods for Imputing Non-Wetting Storm Surge to Improve Hazard Characterization. *Water*, 12(5): 1420. DOI: <https://doi.org/10.3390/w12051420>.
- Shuka, L., Çullaj, A., Shumka, S., Miho, A., Duka, S. and Bachofen, R. (2011). The Spatial and Temporal Variability of Limnological Properties of Bovilla Reservoir (Albania). *Water Resour. Manag.*, 25(12): 3027-3039. DOI: <https://doi.org/10.1007/s11269-011-9788-z>.

- Shults, R., Urazaliev, A., Annenkov, A., Nesterenko, O., Kucherenko, O. and Kim, K. (2020). Different approaches to coordinate transformation parameters determination of nonhomogeneous coordinate systems. *Environ. Engin. (Lithuania)*, enviro.2020.687. Vilnius: VGTU. DOI: <https://doi.org/10.3846/enviro.2020.687>.
- Shumka, S., Kalogianni, E., Šanda, R., Vukić, J., Shumka, L. and Zimmerman, B. (2020). Ecological particularities of the critically endangered killifish Valencia letourneuxi and its spring-fed habitats: A long-lost endemic species of south Albania. *Knowl. Manag. Aqua. Ecosyst.*, 2020-January (421): 45. DOI: <https://doi.org/10.1051/kmae/2020036>.
- Skliar, I., Skliar, V., Klymenko, A., Sherstiuk, M. and Zubtsova, I. (2020). Growth signs of Nymphaea Candida in various ecological and cenotic conditions of Desna Basin (Ukraine). *AgroLife Sci. J.*, 9(1): 316-323.
- Skliar, I., Skliar, V., Sherstiuk, M. and Zubtsova, I. (2023). Dimensional characteristics of Nymphoides Peltata (S.G. Gmel.) Kuntze in different ecological and cenotic conditions of the basin's water bodies Desna River (Ukraine). *Int. Multidisc. Sci. GeoConf. Surv. Geol. Min. Ecol. Manag., SGEM*, 23(3.2): 103-110. DOI: <https://doi.org/10.5593/sgem2023V/3.2/s12.13>.
- Stokes, K., Poate, T., Masselink, G., King, E., Saulter, A. and Ely, N. (2021). Forecasting Coastal Overtopping at Engineered and Naturally Defended Coastlines. *Coast. Eng. J.*, 164: 103827. DOI: <https://doi.org/10.1016/j.coastaleng.2020.103827>.
- Tanim, A.H., Goharian, E. and Moradkhani, H. (2022). Integrated Socio-Environmental Vulnerability Assessment of Coastal Hazards Using Data-Driven and Multi-Criteria Analysis Approaches. *Sci. Rep.*, 12: 11625. DOI: <https://doi.org/10.1038/s41598-022-15237-z>.
- Tikhonova, L.P., Goba, V.E., Kovtun, M.F., Tarasenko, Y.A., Khavryuchenko, V.D., Lyubchik, S.B., and Boiko, A.N. (2008). Sorption of metal ions from multicomponent aqueous solutions by activated carbons produced from waste. *Russ. J. Appl. Chem.*, 81(8): 1348-1355. DOI: <https://doi.org/10.1134/S1070427208080065>.
- Trotta, F., Federico, I., Pinardi, N., Coppini, G., Causio, S., Jansen, E., Iovino, D., and Masina, S. (2021). A Relocatable Ocean Modeling Platform for Downscaling to Shelf-Coastal Areas to Support Disaster Risk Reduction. *Front. Mar. Sci.*, 8: 642815. DOI: <https://doi.org/10.3389/fmars.2021.642815>.
- Wei, S., Han, G., Chu, X., Sun, B., Song, W., He, W., Wang, X., Li, P., and Yu, D. (2021). Prolonged Impacts of Extreme Precipitation Events Weakened Annual Ecosystem CO₂ Sink Strength in a Coastal Wetland. *Agric. For. Meteorol.*, 310, 108655. DOI: <https://doi.org/10.1016/j.agrformet.2021.108655>.
- Wei, Z. and Nguyen, H.C. (2022). Storm Surge Forecast Using an Encoder–Decoder Recurrent Neural Network Model. *Journal of Marine Science and Engineering*, 10(12): 1980. DOI: <https://doi.org/10.3390/jmse10121980>.
- Xie, W., Xu, G., Zhang, H. and Dong, C. (2023). Developing a Deep Learning-Based Storm Surge Forecasting Model. *Ocean Modelling*, 182: 102179. DOI: <https://doi.org/10.1016/j.ocemod.2023.102179>.
- Xuan, T.L., Manh, H.L., Ba, H.T., do Van, D., Vu, H.T.D., Wright, D., Bui, V.H. and Anh, D.T. (2022). Wave Energy Dissipation through a Hollow Triangle Breakwater on the Coastal Mekong Delta. *Ocean Eng.*, 245: 110419. DOI: <https://doi.org/10.1016/j.oceaneng.2021.110419>.

- Yaroshenko, N., Skliar, V. and Rosenthal, G. (2023). Evaluation of ontogenetic and vital structures of *Stellaria Holostea* L. in beech forests in the South of Low Saxony, Germany. *Int. Multidisc. Sci. GeoConf. Surv. Geol. Min. Ecol. Manag., SGEM*, 23(3.2): 325-332. DOI: <https://doi.org/10.5593/sgem2023V/3.2/s14.40>.
- Zhang, C., Yin, K., Shi, X. and Yan, X. (2021). Risk Assessment for Typhoon Storm Surges Using Geospatial Techniques for the Coastal Areas of Guangdong, China. *Ocean Coast. Manag.*, 213: 105880. DOI: <https://doi.org/10.1016/j.ocecoaman.2021.105880>.
- Zubtsova, I. and Skliar, V. (2023). Population analysis of medicinal plants of the floodplain of the Seim River (Sumy Region, Ukraine). *Int. Multidisc. Sci. GeoConf. Surv. Geol. Min. Ecol. Manag., SGEM*, 23(3.2): 187-194. DOI: <https://doi.org/10.5593/sgem2023V/3.2/s12.24>.

Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>
Conceived and designed the research or analysis	Yes	No	Yes
Collected the data	Yes	Yes	Yes
Contributed to data analysis & interpretation	Yes	No	No
Wrote the article/paper	Yes	Yes	Yes
Critical revision of the article/paper	Yes	No	No
Editing of the article/paper	No	Yes	Yes
Supervision	Yes	No	No
Project Administration	Yes	No	No
Funding Acquisition	No	No	No
Overall Contribution Proportion (%)	50	25	25

Funding

No financial support was received for the research and writing of this article.

Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge

The author(s) solemnly declare(s) that this research has not involved Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

Research involving Plants

The author(s) solemnly declare(s) that this research has not involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children

The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

Competing Interests/Conflict of Interest

Author(s) has/have no competing financial, professional, or personal interests from other parties or in publishing this manuscript. There is no conflict of interest with the publisher or the editorial team or the reviewers.

Attribution and Representation

All opinions and mistakes are the author(s)' own and cannot be attributed to the institutions they represent. The publisher is also not responsible either for such opinions and mistakes in the text or graphs or images.

Declaration of the Use of AI

During the preparation of this work, the author used no AI tool to assist the script translation and proof reading.

Rights and Permissions

Open Access. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

To see original copy of these declarations signed by Corresponding/First Author (on behalf of other co-authors too), please download associated zip folder [Declarations] from the published Abstract page accessible through and linked with the DOI: <https://doi.org/10.33002/nr2581.6853.080119>.